

FAILURE ANALYSIS OF SOLID ROCKET APOGEE MOTORS

Prepared for:

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91103

(NASA-CR-128354) FAILURE ANALYSIS OF SOLID
ROCKET APOGEE MOTORS Final Report P.J.
Martin (Stanford Research Inst.) Sep. 1972
56 p



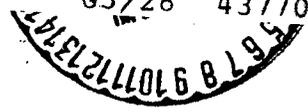
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Menlo Park, California 94025 - U.S.A.



Final Report

September 1972

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PASADENA, CALIFORNIA 91103

CONTRACT 953298

SRI Project 1614

"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology sponsored by the National Aeronautics and Space Administration under Contract NAS7-100."

ERRATA

Contract 953298 Final Report

Failure Analysis of Solid Rocket Apogee Motors

Project No. MSU-1614

Stanford Research Institute

Menlo Park, California

- p. 7, par. 2 "failure of review"
 should read
 "failure review"
- p. 9, par. 3 "TW-479"
 should read
 "TE-479"
- p. 11, Column for TE-M-521 Motor, "9"
 heading should read
Number Flown "4"

ABSTRACT AND SUMMARY

This study to identify problem areas of flight reliability of solid rocket apogee motors began with analysis and summation of relevant data acquired from participating contractors and a literature search. The analysis followed five selected motors (SVM-1, SVM-2, FW-4, TE-364-3, and TE-521) through initial design, development, test, qualification, manufacture, and final flight reports.

The summation was delivered to the motor manufacturers (Aerojet, Thiokol, and United Technology Center) for review and enlargement. An audit was conducted at their plants to complement the literature search with firsthand observations of the current philosophies and practices that affect reliability of the motors. A second literature search emphasized acquisition of spacecraft and satellite data bearing on solid motor reliability.

It was concluded that present practices at the plants yield highly reliable flight hardware. Reliability can be further improved by new developments of aft-end bonding and initiator/igniter nondestructive test (NDT) methods; a safe/arm device; and an insulation formulation. Minimum diagnostic instrumentation is recommended for all motor flights. Surplus motors should be used in margin testing. Criteria should be established for pressure and zone curing. The motor contractor should be represented at launch. New design analyses should be made of "stretched" motors and spacecraft/motor pairs.

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LIST OF ABBREVIATIONS

ABM	Apogee Boost Motor
AEDC	Arnold Engineering Development Center
AFRPL	Air Force Rocket Propulsion Laboratory
CPFF	Cost-Plus-Fixed-Fee
CPIA	Chemical Propulsion Information Agency
CTPB	Carboxyl-Terminated Polybutadiene
DDC	Defense Documentation Center
DDT&E	Design, Development, Test, and Evaluation
"Ex-Design"	Environmental conditions beyond those allowed for in the motor design
FMEA	Failure Modes and Effects Analysis
GE	General Electric
L/D	Length/Diameter Ratio
NDT	Nondestructive Test
PBAN	Polybutadiene Acrylonitrile
Q.A.	Quality Assurance
RFQ	Request for Quotation
S/A	Safe/Arm Device
"Stretched"	A spherical motor design of increased performance as a result of adding a cylindrical section of case and propellant between the hemispheres

INTRODUCTION

By late 1970 five synchronous satellite flights, one Surveyor flight, and one Scout flight had failed during the solid rocket upper stage or apogee boost motor (ABM) operation. This raised serious concern and questions related to the reliability of this class of high performance motors. For the synchronous satellites it is safe to assume a conservative minimum of \$10 million loss per flight, for a total loss of \$50 million. Such satellites are the largest single projected user of these motors to 1980, principally for communications.

NASA and the Department of Defense had fully developed the technology, materials, and documentation for designing, manufacturing, and testing this class of motors; none of the flown designs pressed the state of the art, even though they were high performance. The failures were also puzzling and of concern because no patterns were apparent except that the observed anomalies occurred after more than 4 seconds of burn.

This study was initiated to obtain as much detail as possible on the pertinent motors and their performance to determine whether there were deficiencies in the technology or in its application that might have caused a reduction of reliability.

Five specific motors involved in anomalous flights were selected for detailed review from their inception to flight delivery. Data and information were acquired and analyzed for these and related, pertinent motors. Preliminary recommendations thus developed were in hand during the conduct of plant audits of the three participating motor contractors--Aerojet, Thiokol, and United Technology Center--and during visits to NASA launch vehicle offices and spacecraft contractors. The findings were reviewed in light of spacecraft/motor interface data developed in a parallel Jet Propulsion Laboratory systems study of the spacecraft and launch vehicle.

Areas of research and development to improve reliability were identified. A failure modes and reactions tabulation was prepared to summarize the experience of the motor contractors. This tabulation is a motor designer's checklist of actual experienced failure causes and the design,

process, and inspection steps that have proven useful in avoiding repetition of the failures. Design features to improve reliability were identified. Changes in procurement practices to improve reliability were identified. Recommendations were ranked for their impact on reliability and for their implementation cost and schedule.

CONCLUSIONS

1. The three solid rocket apogee motor contractors participating in this study have documented, and practice, design, manufacture, and inspection procedures that yield highly reliable flight hardware.
2. Four recommendations were identified as of value to current flight programs, attainable at modest cost and achievable within one year or less. These are:
 - Judicious use of minimum diagnostic instrumentation on all solid ABMs and upper stage motors
 - The presence of a motor contractor representative during launch preparation
 - A new review of current spacecraft/motor pairs
 - New analyses of "stretched" motors.
3. Two studies were identified that could lead to improvement in motor reliability at moderate cost and within one year. These were:
 - Use of over age and/or surplus motors for margin testing
 - Development of design criteria for the application of zone and pressure curing.
4. Four material and subsystem development and qualification programs could be implemented at significant cost during a two to five year span to improve reliability. They are:
 - Aft-end bonding, boots, propellant quality, and NDT methods improvement
 - Development and qualification of a new elastomeric insulation formulation
 - Development of initiator/igniter NDT methods
 - Development and qualification of a safe/arm device with integral transducer.

5. A checklist of incurred failures and corrective actions taken was prepared to summarize industry experience with these high performance motors. The list should be equally useful to the buyers and sellers of apogee motors.

TECHNICAL DISCUSSION

Motors Selected for This Study

Five specific motors (see Table 1) were selected to encompass the broadest possible representation of:

- Motor design concepts
- Solid rocket technology
- Motor procurement practices
- Rocket motor contractors
- Spacecraft contractors
- Launch vehicle contractors
- Launch vehicle offices

Each selected motor was involved in an anomalous flight, and it was presumed that the flight failure review board had assembled all available documentation and data and had assessed possible causes for the anomalies. It was not intended to make a redetermination of the causes, but it was hoped that this study could benefit from the documentation and detail assembled by the failure review teams.

The FW-4S motor was selected to include the all-solid launch environment of the Scout, and spin stabilization. The SVM-1 was selected as representative of the lower size limit of apogee motors. The SVM-2 motor is mid-range in size and uses a composite motor case. The TE-364-3 is representative of large, spherical, titanium-case motors. Finally, the TE-521 is representative of "stretched" spherical motors.

The included technology and design concepts of current interest are:

- Silver-infiltrated tungsten and graphite throat inserts
- Free-standing graphite throats
- A wide range of nozzle submergence
- Composite and titanium motor cases

Table 1

SELECTED MOTORS AND FLIGHTS

<u>Motor Designation/ Contractor</u>	<u>Spacecraft/Vehicle</u>	<u>Failure</u>	<u>Remarks</u>
Apogee Motors SVM-1/Aerojet	INTELSAT II (F-1) DELTA	Rocket motor aft-end insulation and case failure at -30° F.	Actual inflight low temperature excursion was beyond specification limits. Failure simulated in ground tests after flight.
SVM-2/Aerojet	INTELSAT III (F-8)/ DELTA	Specific failure mode not authenticated.	Sudden data dropout; sun angle data imply motor anomaly.
TE-521/Thiokol	SKYNET I/DELTA	Specific failure mode not authenticated. Propellant/insulation bond failure postulated.	Sudden data dropout; Doppler data imply motor anomaly.
Upper Stage Motors TE-364-3/Thiokol	INTELSAT III (F-5)/ DELTA	Specific failure mode not authenticated. Massive case rupture postulated.	Breakup of stage and payload noted; no telemetry data during incident.
FW-4/United Technology	OV-3/SCOUT	Graphite throat breakup.	One earlier quality control motor had cracked throat.

- A range of length/diameter ratios
- Booted and fully bonded grains
- CTPB and PBAN propellant and liner formulations
- Pellet and pyrogen igniters
- Motors integral with and separable from the spacecraft
- A wide range of motor sizes.

For each of the selected motors all available documents were sought-- from initial request for proposal or quotation through delivery of flight motors and special tests subsequent to the anomalous flights. A parallel JPL systems study was established to obtain and analyze spacecraft and launch vehicle data pertinent to the selected flights.

The failure of review board for the FW-4S determined that breakup of the graphite nozzle throat insert had occurred. A development program resulted in an improved nozzle design and no similar problem has occurred in 44 consecutive flights with this design.

The SVM-1 motor suffered an aft-end failure and nozzle loss resulting from exposure of these motor parts to low temperatures well below the designed-for environment. The failure was duplicated in ground static tests, heaters were added to the spacecraft to maintain the design environment, and users have added a nozzle low temperature exposure requirement to some qualification tests in later motor programs.

The limited data from the SVM-2, TE-364-3, and TE-521 flights did not allow the failure review board to ascertain solid motor failure as the cause, although such failures were one of the possible causes. These flights did reinforce the frequently stated need for limited diagnostic motor instrumentation on upper stage and apogee motors.

Motor Program Documentation

The FW-4 and TE-364 motors were designed, developed, and qualified on fully funded Air Force and NASA programs, so their documentation was found reasonably complete and available from the Defense Documentation Center and NASA's Scientific and Technical Information Facility. The JPL library was also of significant value for reports on these and related motors.

For the SVM-1, SVM-2, and TE-521 motors, the motor and spacecraft contractors contributed most of the documentation in very evident cooperation in the literature review phase of this study.

It was a noteworthy conclusion of this particular document gathering attempt that the developers of commercially funded motors do not voluntarily contribute their technical material to the CPIA information exchange program. The selected materials and formulations for this class of high performance motors are derivatives of government-funded developments and therefore can be found in the CPIA literature with some diligent searching. However, the design techniques and certain design features of these motors are a significant loss to the CPIA files. No solution to this problem is readily apparent.

A complete set of documents was not available for any one of the motors, but design and program similarities were sufficient for the comparisons being made. The kinds of documents obtained and reviewed are shown in the following list:

- General reliability
- Materials research
- Propellant research
- Motor DDT&E
- Launch failures
- Special motor tests
- AEDC altitude static tests
- Motor program final reports
- Motor log books
- Motor program proposals
- Spacecraft motor RFQ's
- Vehicle and motor descriptions.

A cursory review of the documents from initial RFQ through flight deliveries yields a picture of repetition, especially in the requested submissions of integrated test plans, reliability block diagrams, quality assurance plans, reliability program plans, and quality control engineering plans, wherein much of the same information is restated in different formats.

Where some future program is dependent entirely on private funding, there should be an opportunity for a spacecraft user to specify an exemplary minimum document package that contains only test data and commits the seller to use of his previously documented manufacturing and quality maintenance practices.

The submitted failure modes and effects and analyses (FMEA) are questionable in their conveyed reassurances in some instances. Uniform emphasis is not given to equally likely failure causes, and the FMEAs reflect each contractor's individual experience. A possible solution to this documentation problem is offered subsequently in a generalized failure modes and reactions tabulation that has lasting value as a check-list of precautions that have or can be taken from initial design through delivery.

Selected and Related Motor Programs

The five selected motor programs were based on some earlier motor developments, and these earlier programs were included to fully develop the technology, design, and manufacture evolution. The TW-479 was "stretched" to the TE-521 design; the FW-3 was "shortened" to the FW-4; and the TE-360/364 Surveyor has gone through several modifications including the TE-364-3, as examples.

The motor programs included in this study ranged in cost from in excess of \$10 million for the TE-360/364 Surveyor/Burner II/Delta family to about \$300 thousand for the TE-479. In the former program, more than 100 motors were manufactured; in the latter, 10 motors loaded from a single propellant batch were enough for six development and qualification firings and four flight deliveries. Typical apogee motor programs today call for four to seven development and qualification test motors plus the flight requirements. The typical dollar value of these programs ranges from \$600,000 to \$1,200,000, with a contract performance period from one to three years. Schedule is dependent mostly on anticipated spacecraft or satellite launch schedules.

Significant similarities of the programs follow:

- The designs are conservative in that none reflect the ultimate state of the art in materials, design, and formulation for achieving the highest possible performance.
- Propellants, materials, components, and processes have been qualified in other programs and have extensive manufacturing and inspection histories.

- Delivery schedules (except for first inert motor or mockup) are not tight.
- Competition is fixed price.
- Manufacturing and quality assurance plans, and FMEAs are similar.
- Motor contractors are conscious of moisture effects, and the advantages of pressure cure.

There are significant program and design differences among the motors:

- Case materials
- Nozzle inserts and design concepts
- Grain configurations
- Safe/arm and igniters
- Balance of effort subcontracted and in-house
- Degree of integration of ABM with other motor programs in each plant.

Pertinent information and selected motor descriptive data are summarized in Tables 2 and 3.

Audit of Motor Contractors

The audit plan, as initially developed, allowed for five days of plant visit. Subsequently, it was found possible to reduce the time required at Thiokol to four and one-half, at Aerojet to three, and at United Technology Center to three and one-half days because much detail was contained in the documents submitted in advance by the motor contractors. The significant elements of the audit plan (mechanics, leads, checklists, and comparisons) are outlined below.

Mechanics of Audit Plan

- Prepare and forward literature search findings, and approved audit plan to participating contractors.
- Arrange visits to plants.
- Conduct visits.

Table 2

SOLID ROCKET APOGEE AND UPPER STAGE MOTOR HISTORY

Motor Designations	Design, Development, and Qualification			Use of Flightweight Designs					Notes on Flights and Status
	Start Date	Number of Months	Number of Firings	First Flight	Latest Flight	Number Made	Number Tested	Number Flown	
Aerojet									
SVM-1 (HS-303A)*	8/65	9	18	10/66	9/67	31	24	4	INTELSAT II S/C; 1 failure due to S/C temp. excursion below spec. limits set for motor; 3 successes since heaters added to S/C
SVM-2*	2/67	12	20	9/68	7/70	28	20	8	INTELSAT III S/C; 1 failure with mode not authenticated-motor anomaly implied; 2 no-test; 5 successes
SVM-4/4A	2/69	18	12	2/71	6/72	22	14	4	SVM-4 "stretched" to SVM-4A after 3 development tests; INTELSAT IV S/C 4 successes
SVM-5	5/71	under-way	7	--	--	3	3	--	Qualification to be completed 11/72; SMS S/C
JPL									
JPL-SR-28-1/3	1/63	44	35	12/66	8/69	53	35	4	ATS S/C - B through E; 3 successes; 1 no-test; -3 titanium flight version; -1 steel development testing
Thiokol									
TE-M-479	5/66	9	6	7/68	--	10	6	1	RAE S/C; 1 success
TE-M-521*	5/67	12	5	11/69	2/71	11	5	9	Skynet I S/C; 1 failure with mode not authenticated-motor anomaly implied; 3 successes
TE-M-521-5	2/72	under-way	2	--	--	3	2	--	"Beefed-up" version of TE-521 for IMP-H and -J S/C
TE-M-616	6/72	under-way	5	--	--	--	--	--	New program; ABM for CTS S/C
TE-M-360/364; 364-1	4/61	39	50	6/66	1/68	65	50	7	Surveyor S/C retro; 1 signal lost at tailoff, 5 successes, 1 no-test
TE-M-364-3/2*	6/65	12	12	9/66	2/71	43	12	24	Upper stage Delta...3 vehicles and Burner II stage; 1 failure with mode not authenticated, 22 successes; 1 no-test
TE-M-364-4	3/68	39	11	3/72	--	--	11	1	Upper stage Delta...4 vehicles; 1 success
United Technology									
FW-3	11/62	8	2	--	--	--	--	--	Predecessor to FW-4
FW-4 (SR57-UT-1)*	5/64	9	17	5/65	6/72	88	17	62	Scout and Delta upper stage; 1 failure due to nozzle throat insert; 44 successes since nozzle design change
FW-5	11/70	22	9	--	--	13	9	--	Qualification to be completed 9/72; first flight is 11/72 with TELESAT S/C

* Selected motors for this study.

ABBREVIATIONS FOR TABLE 3

S-PB	Silica-Filled Polybutadiene Rubber
FWG	Filament-Wound Glass
BPN	Boron-Potassium Nitrate Pellet or Grain
FRP	Filament-Reinforced Plastic
ITWA	Externally-Insulated Thin-Wall Aluminum
CTPB	Carboxy-Terminated Polybutadiene
HDG	High Density Graphite
Ag/W	Silver-Infiltrated Tungsten
PU	Polyurethane
A-S-BN	Asbestos-Silica-Buna-N Rubber
MEOP	Maximum Expected Operating Pressure
PIP	Polyisoprene
BAN	Butadiene Acrylonitrile
PBAN	Polybutadiene Acrylic Acid CoPolymer

Table 3

SELECTED SOLID ROCKET MOTOR PERFORMANCE AND PRINCIPAL DATA

Motor Designations	Performance							Motor Case		
	Duration (sec)	Average Thrust (LBF.)	Max. Thrust (LBF.)	Thrust Envelope	MEOP	Loaded Weight (lbs)	Expended Weight (lbs)	Diameter (in.)	Length (in.)	Material
Aerojet										
SVM-1 (HS-303A)*	16.2	2,906	3,240	Neut.	465	193	27	18.0	15.9	FWG
SVM-2*	27.6	3,140	4,830	Regr.	509	350	41	22.3	35.0	↓
SVM-4/4A	33.8	12,480	15,150	Regr.	929	1,557	123	36.7	60.3	↓
SVM-5	37.3	5,060	7,230	Prog.	760	705	55	30.0	35.5	↓
JPL										
JPL-SR-28-1/3	43.3	5,500	6,083	Prog.	260	841	81	28.0	28.8	†
Thiokol										
TE-M-479	18.6	2,380	2,775	Prog.	1,000	175	18	17.4	Sphere	Titanium
TE-M-521*	19.1	3,720	4,470	↓	850	273	24	38.6	↓	↓
TE-M-521-5	↓	↓	↓	↓	↓	275	25	↓	↓	↓
TE-M-616	34.8	5,996	7,277	Neut.	590	800	59	27.3	48.7	↓
TE-M-364	41.0	8,376	9,500	Prog.	570	1,315	138	37.0	Sphere	D6AC
TE-M-364-1	40.2	8,930	10,000	Neut.	561	1,339	138	↓	↓	↓
TE-M-364-3/2*	41.6	9,983	10,500	↓	650	1,580	138	↓	↓	↓
TE-M-364-4	42.7	15,100	16,870	↓	707	2,465	168	↓	68	Titanium
United Technology										
FW-3	38.5	5,760	6,410	Neut.	550	827	67	18.0	56	FWG
FW-4S (SR-57-UT-1)*	29.3	5,910	6,600	↓	796	664	62	19.6	40.4	↓
FW-5	39.0	4,250	5,600	Prog.	907	645	63	27.2	44.2	↓

Motor Designations	Nozzle				Igniter			Propellant Grain			Insulation	
	Throat Area (sq.in.)	Expansion Ratio	Insert Material	Submergence	Type	Location	Case Material	Configuration	Binder	Percent of Solids	Form	Material
Aerojet												
SVM-1 (HS-303A)*	4.2	33	Ag/W	Slight	BPN	Fore	FRP	CONOCYL	CTPB	88	Premolded	S-PB
SVM-2*	6.0	28	↓	~20%	↓	↓	↓	FINOCYL	↓	↓	↓	↓
SVM-4/4A	9.3	40	↓	None	↓	↓	↓	FINOCYL	↓	↓	Premolded	↓
SVM-5	5.4	27	↓	~20%	↓	↓	↓	CONOCYL	↓	↓	W/Aft Boot	↓
JPL												
JPL-SR-28-1/3	13.1	35	HDG	~25%	ALCLO	Fore	Al	Cylindrical	PU	80	Sheet	BAN
Thiokol												
TE-M-479	1.5	61	G-90	~15%	2-Pyro	Aft	Titanium	8-Pt Star	CTPB	86	Premolded	PIP
TE-M-521*	2.6	58	↓	Slight	↓	↓	↓	↓	↓	↓	W/Boots	↓
TE-M-521-5	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
TE-M-616	2.1	42	↓	Slight	1-Pyro	Fore	↓	↓	↓	88	↓	↓
TE-M-364	9.0	53	↓	~40%	↓	↓	Al	↓	↓	86	↓	A-S-Bn
TE-M-364-1	8.5	53	↓	↓	↓	↓	Al	↓	↓	↓	↓	↓
TE-M-364-3/2*	8.5	53	↓	↓	↓	↓	Titanium	↓	↓	↓	↓	↓
TE-M-364-4	14.5	31	↓	↓	↓	↓	↓	↓	↓	↓	↓	PIP
United Technology												
FW-3	6.7	30	ATJ	Slight	Rocket	Fore	Steel	Cylindrical w/Transverse slot	PBAN	83.5	Premolded	S-BN
FW-4 (SR-57-UT-1)*	4.1	53	G-90	↓	↓	↓	ITWA	↓	↓	84.5	↓	↓
FW-5	3.8	60	↓	↓	↓	↓	Steel	Cylindrical	↓	↓	↓	↓

* Selected motors for this study.

† -1 Version is steel.

-3 Version is Titanium.

- Day 1--SRI/JPL joint visit. Discussions with plant management, reliability chief, motor program manager, chief design engineer, quality assurance manager, and production manager. Obtain contractor comments, reactions, additions, and modifications to audit scope. Plant tour.
- Day 2--Study of locally available reports and documents identified in literature search and Day 1 discussion.
- Day 3--Observation of inspection and quality assurance (Q.A.) operations.
- Day 4--Observation of manufacturing operations.
- Day 5 (A.M.)--Pick up remainder of inspection, Q.A., and manufacturing operations.
- Day 5 (P.M.)--Initial screening of analyses and interpretations with plant management.
- Prepare draft of audit findings and forward to plants for formal approval or modification.

Leads Pursued During Audit

- Motor design
 - Igniter-case-adhesive heat flow
 - Insulation exposure and erosion during burn
 - Web at critical time
 - Special adhesion requirements
 - Spin and acceleration trapping of slag
 - Spin and acceleration grain and case-bond stresses
- Motor manufacture
 - Motor case reloading
 - Winter and summer loading-relative humidity
 - Solvent use and removal
 - Liner storage age, humidity, and temperature
 - Motor insulation installation
 - Zone cure
 - Pressure cure

- Mandrel installation and removal
- Igniter acceptance testing
- Availability of polymers
- Preparation for flight
 - Motor contractor representation at launch
 - Motor installation
 - Igniter installation
 - Motor instrumentation
 - Motor storage, surveillance, and aging
 - General Electric study on small motors out of Langley AFB.

Check List for Discussions with Plant Management

- Development program/flight project
 - Schedule - stretched, compressed, flexible
 - Cost - fixed price, CPFF
 - Design - degree of change from preceding motor
- Motor characteristics
 - Performance - weight, volume, mechanical properties, L/D
 - Case - in-house, subcontract
 - Attachments - spacecraft-unique, fore, aft
 - Insulation - case integrity
 - Nozzle - insert, submergence, balancing, retention
 - Grain - configuration, stress
 - Igniter - assembly, acceptance, NDT
- Formulate
 - Propellant - history, burn rate, mechanical properties, processibility, storage and liner
 - Adhesives - commercial, in-house, proprietary

- Build motors
 - Test - development and qualification
- Test
- Qualify
- Produce - traceable, no change, value engineering, performance improvement
- Inspect - contractor, prime, government agency
- Accept - review board
- Store - plant, spacecraft plant, launch site
- Ship - commercial, air, surface, military
- Install - contractor, prime, launch crew
- Use.

Check List for Discussions with Motor Designers

- Spacecraft-imposed limitations
 - Envelope dimensions
 - Attach fittings
 - Motor external temperatures
 - Center of gravity
 - Spin balance
 - Initiator installations
 - Magnetic properties
 - Space vacuum exposure
- Performance constraints
 - Total impulse
 - Loaded motor mass
 - Expended motor mass
 - Thrust-time envelope
 - Use temperature range
 - Impulse adjustability

- Reproducibility
- Space vacuum ignition
- Launch vehicle constraints
 - Liquid rocket vehicle
 - Solid rocket vehicle
 - Acceleration and launch loads
- Procurement and program limitations
 - Development schedule
 - Development cost
 - Delivery schedule
 - Delivery cost
 - Midprogram changes
- Environment
 - Air shipment
 - Rail/truck shipment
 - Storage temperatures
 - Storage life

Checklist for Discussions and Observations--Inspection and Quality Assurance

- Propellant ingredients
 - Ammonium perchlorate
 - Aluminum powder
 - Burn rate catalyst
 - Polymer
 - Crosslinker
 - Cure catalyst
 - Plasticizer
- Motor lining and loading
 - Processing aids
 - Silica

- Carbon black
- Process solvents
- Cleaning solvents
- Inert parts fabrication
 - Glass filament
 - Glass fabric
 - Glass tape
 - Molding compound
 - Case and nozzle forgings, or
 - Case and nozzle shell
 - Fiberglass case
 - Fiberglass case inserts
 - Igniter inert parts
 - Molded insulation
 - Sheet insulation
 - Nozzle insert
- Igniter fabrication
 - Safe/arm
 - Initiator
 - Igniter pellets or granules
- Motor assembly
 - "O" rings
 - Sealant
 - Adhesive
 - Nozzle closure.

Checklist for Observations at Plant

- Inerts preparation
 - Case mandrel fabrication
 - Insulation molding

- Insulation application
- Filament winding
- Composite build-up
- Case manufacture
- Nozzle manufacture
- Case preparation
- Insulation bonding
- Liner preparation
- Liner application
- Motor loading and assembly
 - Propellant preparation
 - Motor loading
 - Propellant curing
 - Mandrel removal
 - Propellant trimming
 - Motor balancing
 - Nozzle alignment
- Quality assurance
 - Inspection stations
 - X-ray and NDT (emphasis on flaw detection and resolution)
 - Chemical laboratory
 - Physical test laboratory
 - Ballistic test laboratory
 - Static test site
- Shipping and storage
 - Packing
 - Storage and handling
 - Moisture control-winter and summer.

Comparisons to be Sought on the Selected Motors

- History
 - Motor lineage
 - Failure modes
 - Extent and nature of problems
 - Imposed design limitations
- Manufacturing
 - Manufacturing processes and flow
 - Extent of subcontracting
 - Vendors
 - Degree of postqual vendor control
 - Inspection and acceptance
- Materials selection
 - Elastomeric insulation
 - Hard insulation
 - Nozzle inserts
 - Seals
 - Propellant ingredients
 - Liner ingredients
 - Adhesives and bonding agents
- Design
 - Depth of design analyses
 - Extent of design modification
 - Design safety factors.

Audit Findings

A conscientious effort was made to be objective in the audit by comparing the significant plant observations with the literature findings, but some subjectivity may have been introduced by the many discussions and expressed opinions that were weighed in the mind of the principal investigator.

The observed conditions of design, manufacture and inspection in this 1972 audit represent real progress over the informal, but similar, audit by the principal investigator in 1965-66, the era of inception of most of the motors of current interest.

Noteworthy audit findings not limited to a single motor contractor are:*

- The effects of moisture on CTPB propellant and liner formulations are known, as evidenced by the processing steps taken to maintain dry, inert conditions from insulation surface preparation through propellant cast and cure. (The question of insulation moisture content and its diffusion to the liner as a consequence of a severe concentration gradient was raised subsequent to the audit and remains unresolved.)
- The subcontracted manufacture of cases, nozzles, and other inerts is under strict and adequate control by the motor contractors.
- Cylindrical and star grain perforations present significant differences in processing ease, volumetric loading, off-loading, and balancing.
- Pressure cure cycles to obtain essentially stress/strain free grains at ambient temperature following cure are understood and applied where needed by the motor contractors.
- The NDT facilities available at each plant are capable of anomaly resolution of voids and porosity below the specified tolerable maxima, but radiographic data interpretation between facilities is not uniform. Detection of case bond separation at ambient temperatures may still present a problem at times.
- Each motor contractor has developed a unique combination of materials and design concepts capable of delivering high performance with a high degree of reliability.

The motor contractors expressed noteworthy opinions on problems that can be partially or completely solved by the motor buyers.

* The specific audit findings in some instances were considered proprietary to the visited contractors and were not documented in this report.

- Minimum diagnostic instrumentation is needed on every upper stage and apogee motor to supply data that can be used in corrective actions to determine if the motor is the cause of the spacecraft or vehicle failure.
- The safe/arm (S/A) requirement for a redundant mechanical and electrical capability is not justifiable and prevents the use of lighter, completely adequate S/As.
- The maximum skin temperature requirements should be determined by the spacecraft needs instead of opinions on what the motor case will withstand.
- The use of lower than design temperatures for X-ray inspection can cause bond failures.
- Some of the requested or required qualification tests and inspections do not achieve the objectives desired:
 - Post fire balance is not valid because the present static-test rigs cannot obtain a sufficiently precise dynamic balance reading immediately after firing the spinning motor. If the motor is stopped and cooled, pieces of char and insulation can loosen and fall. If these are brushed out, the test does not reflect flight conditions.
 - Vibration applied through a hardmount does not reproduce the dynamic loads of the launch vehicle skin and attach structure, with its unique resonances.
 - Drop tests are only a gross approximation of launch or separation shock.
 - Acceleration during spin and burn is not within the capabilities of existing test facilities, and release of the burning motor to allow it to travel a few inches to a forward stop position introduces unreal transient loads.

Failure Modes and Reactions--An Experience Summary

The components, materials, and subsystems of solid motors have incurred failures in development tests and flights. These failures have resulted in a variety of corrective actions and precautions. It is now fairly common practice to include a detailed FMEA for each motor program. The FMEAs of the selected and related motors were duplicative in some areas and somewhat hypothetical in assigning causes for some failures.

The following tabulation (Table 4) of failure modes and reactions includes only actual failures, failure causes, and corrective actions that have been taken to prevent reoccurrence. These failures have been observed at one or more levels of inspection and test from incoming receipt through motor operation. The table does not include failures that have been identified with environmental exposures or excursions beyond those allowed for in the design ("Ex-Design") of the motors. It does not attempt to attenuate the first effects of the failures by estimating the final effects in terms of mission degradation or total loss.

In this generalized form, many motor and component tests have been reduced to a checklist for motor designers and manufacturers.

Table 4 Key

AGENT	1 Ignition and initial pressurization 2 Normal motor operation 3 Tailoff and sliver burning 4 Flight loads 5 Storage and shipping
FIRST EFFECT	1 Increased propellant burning surface 2 Chamber exposed to propellant flame 3 Chamber rupture 4 Chamber exterior overheating 5 Nozzle exterior overheating 6 Thrust vector change 7 Parts ejection 8 Motor distortion or growth 9 Delayed ignition 10 No ignition
REACTIONS-DESIGN	1 Materials selection 2 Materials characterization 3 Materials formulation 4 Stress analyses 5 Thermal analyses 6 Design margins 7 Design tolerances 8 Grain stress relief 9 Nozzle stress relief 10 Positive retention features 11 Redundancy
REACTIONS-PROCESS	1 Bond surfaces preparation 2 Humidity control of operating areas 3 Hermetic sealing of components between operations 4 Low temperature storage of adhesives and elastomers 5 Moisture and volatiles control of ingredients 6 Time limits for storage and between operations 7 Traceability of materials, components and operations 8 Cure cycle control 9 Drawing notes 10 Operator and vendor certification
REACTIONS-INSPECTION	1 Chemical 2 Metallurgical 3 Tensile 4 Ultrasonic 5 Dye penetrant 6 Radiographic 7 Hydroproof 8 Bond strength 9 Dimensional 10 Visual 11 Ballistic 12 Batch formulation 13 On-site vendor surveillance 14 Materials certification

Table 4

APOGEE AND UPPER STAGE SOLID ROCKET MOTOR FAILURE MODES AND REACTIONS

Failure Mode	Causes	Agent	First Effect	Reactions		
				Design	Process	Inspection
Case, Titanium						
Rupture	1. Wrong alloy, defective forging, defective weld, improper heat treat, wrong dimension	1	3	4,5,6,7	7,9,10	2,3,4,5,6,7,9,10,13,14
Structural failure of nozzle or igniter boss	↓	1,2	6			
Skirt structural failure		4	6			
Case buckling	↓	2,3,4	8			
Case, Filament-Wound						
Rupture	5. Wrong filament or resin composition or ratio; irregular filament indexing, tension, or number of turns; curing errors; moisture pickup by filament; over-age resin formulation; poor bonds at component interfaces	1	3	1,2,3,4,5,6,7,10	1,2,4,6,7,8,9,10	1,3,4,6,7,8,9,10,13,14
Case buckling	↓	2,3,4	8			
Structural failure of nozzle or igniter boss	As in 5 above plus wrong alloy, defective forging, improper heat treat, wrong dimension	1,2	6			As above plus 2,5
Skirt structural failure	↓	4	6			
Insulation, Case						
Fracture, tear or delaminate	9. Wrong formulation; wrong lay up; wrong cure or solvent removal cycle; ozone, ultraviolet, or humidity exposure; over-age formulations; wrong surfaces preparation; wrong dimension; wrong mold temperature distribution; inadequate mold release	1,2,5	2	1,2,3,4,5,6,7	1,2,4,5,6,7,8,9,10	1,3,4,8,9,10,12,13,14
Excessive erosion or heat transfer	↓	2,3	4			
Separation from case	As in 9 above plus wrong case surface preparation	1,2,5	2	As above plus 10		
Stress Relief Boot						
Fracture, tear, or delaminate	12. As in 9 above plus incomplete release from insulation and inadequate hinge joint	1,2,5	1	1,2,3,4,6,7,8	1,2,4,5,6,7,8,9,10	1,3,6,8,9,10,13,14
Separation from propellant	↓				1,2,3,4,5,6,7,8,9,10	
Liner						
Inadequate insulation-propellant bond	Wrong formulation, wrong application, wrong cure or solvent removal cycle, overexposure to atmosphere, over-age formulation, wrong insulation surface preparation			1,2,3,6,7,8	1,2,3,4,5,6,7,8,9,10	1,3,6,8,10,12,14
Voids	Air entrapped during application	1,2		1,2,3	5,6,7,10	4,6,10
Propellant Grain						
Fracture	16. Wrong formulation, ingredient purity, or form; overexposure to atmosphere; over-age ingredients; mix, cast, and cure cycle errors	1,2,5		2,3,4,5,6,7,8	2,5,6,7,8,10	1,3,6,9,10,11,12,14
Excessive shrinkage						
Nonhomogeneity		1,2				
Voids or porosity	As in 16 above plus moisture contamination					

Table 4 (Concluded)

Failure Mode	Causes	Agent	First Effect	Reactions		
				Design	Process	Inspection
Propellant-insulation separation	As in 16 above plus liner surface preparation errors	1,2,5	↓	↓	1,2,3,4,5, 6,7,8,9,10	1,4,6,8,9, 10,14
Bore surface contamination	Excessive mold release on Mandrel or over-exposure to atmosphere	1	9	--	7,9,10	10
Nozzle Retention Ring and Exit Cone Shell						
Structural failure and/or ejection	As in 1 above	1,2,4	6	1,2,4,5, 6,7,9,10	7,9,10	2,3,4,5,6, 7,9,10,13,14
Nozzle Exit Cone						
Structural failure and/or ejection	As in 5 above	1,2	6	1,2,3,4,5, 6,7,9,10	1,2,4,6, 7,8,9,10	1,3,4,6,7, 8,9,10,13,14
Abnormal erosion			5			
Nozzle Composite Entrance Cap						
Structural failure and/or ejection			6			
Abnormal erosion						
Nozzle Composite Throat Backup						
Structural failure and/or ejection						
Abnormal erosion						
Nozzle Throat Insert (Silver-infiltrated Tungsten)						
Fracture and ejection	Wrong composition or dimension, infiltration error			2,4,5,6, 7,10	7,9,10	9,10,14
Nozzle Throat Insert (Graphite)						
Fracture and ejection	Wrong composition or dimension, wrong grain structure or orientation, non-homogeneity			1,2,4,5,6 7,9,10	7,9,10	2,3,6,9, 10,11,13,14
Nozzle Throat (Free-standing graphite)						
Fracture and ejection						
Abnormal erosion						
Igniter						
Main charge is analogous to a rocket motor and has the same subsystem and component failure modes and reactions PLUS						
Abnormal pyrotechnic energy release	Wrong formulation and/or granulation, wrong charge weight, overexposure to atmosphere, wrong charge consolidation or packing geometry	1	9 or 10	2,3,6, 7,11,	2,3,5,7, 9,10	9,10,11, 13,14
Abnormal squib energy release						6,11,14
Seals, Nozzle and Igniter						
Leakage	Wrong formulation, wrong dimensions, wrong cure cycle, over-age formulation	1,2	6	4,5,6,7, 10,11	6,7,9	9,14
Bolts, Nozzle and Igniter						
Fracture or Yield	Wrong alloy, defective forming, wrong heat treat, wrong dimension	1	6 or 7	1,4,5,6, 7, 11	7,9	3,9,14

RECOMMENDATIONS

The recommendations developed in the literature reviews and plant audits were ranked for relative costs and implementation schedules. They are listed below and ranked for their potential reliability improvement.

1. Improvement of aft-end bonding, boots, propellant quality, and NDT
2. Minimum diagnostic instrumentation on upper stage and apogee motors
3. Motor contractor representation at launch preparation
4. Use of aged and/or surplus motors for margin testing
5. Design criteria for application of zone and/or pressure curing
6. Development and qualification of new insulation formulation
7. Development of initiator/igniter NDT
8. Development and qualification of safe/arm with integral transducer
9. New review of spacecraft/motor pairs
10. New analyses of stretched motors.

Aft-End Problems

The most frequent single cause for rejection of motors at inspection and the suspected cause of some flight anomalies is bond separation in the motor/insulation/liner/propellant system in the vicinity of the nozzle attach fitting. Where bond failures have occurred without separation of the faces, NDT by radiographic methods is unable to detect such failures. Bond strength at the important aft-end interfaces of case, insulation, and propellant is not measurable in loaded motors by present NDT methods. One technique of some utility is the conditioning of motors to lower temperatures before X-ray to obtain detectable separations where the case bonds have failed without separation at ambient temperature.

This technique can cause cumulative damage and subsequent bond failure if the motor designer is not forewarned of the test temperature extreme and the maximum number of times the motor may be put through this cycle for the several radiographic inspections that occur before flight.

Propellant defects of voids and porosity appear more frequently in the aft end than elsewhere in the grain because the motors are loaded through this end and cured with this end upward. Resolution of specified flaw criteria by radiography is within capability, but disagreement is found in the interpretation of results at the launch sites.

Item 1 is costly and time-consuming, but its potential contribution to reliability improvement warrants its inclusion for consideration. There would be merit in combining it with Item 6 in a new single program to develop an insulation and aft-end design usable for metal and composite motor cases and offering reliable adhesive bonds; mechanically locked periphery at the nozzle attach point, positive physical testing of the insulation/case bond before lining; and nonambiguous NDT of the bonds up to the time of installation of the motor in the spacecraft.

Flight Motor Instrumentation

The reliability record of solid rocket motors and the simplicity of design and operation compared with other subsystems of the spacecraft and launch vehicles has given ABMs and upper stage motors low priority for diagnostic or performance instrumentation.

None of the specific flights selected for this study carried direct measurement capability for the solid rocket motors. The literature review identified a few flights with the solid motor instrumented for external temperatures, but no flights since 1965 that carried chamber pressure measurement capability.

When the solid motor was the most reliable of the launch subsystems and the limited number of telemetry channels were assigned on a priority basis to diagnose other areas of launch vehicle performance, it was perhaps necessary to forego instrumentation of the solid motor. Subsequently, it appears that solid rocket motor diagnostic measurement has been avoided as an economy measure. The elimination of strain gauge installation reduces cost, and the elimination of the postflight data reduction makes a more significant reduction; most vehicles now carry spare telemetry channels. In one instance the spacecraft designer eliminated a planned motor strain gauge because of physical interference with an adjacent structural component.

The rocket motor contractors have frequently expressed their desire for flight diagnostic measurements from their motors to no avail, with resultant compounding of the speculations of failure review boards.

A positive step can be taken on behalf of this expressed desire by the judicious inclusion of limited instrumentation including a chamber pressure transducer on every space motor. A safe/arm device is compulsory for range safety, invariably has access to motor chamber pressure via the igniter and initiator porting, and is necessarily interfaced with the spacecraft by a wiring harness. A piezoelectric transducer is adequate and delivers sufficient electrical signal for the usual telemetry transmitter, if it is determined that resistance strain gauges might place an unacceptable power demand on the spacecraft power supply.

This improvement in reliability can be obtained at low cost per motor and as soon as NASA implements a decision that such diagnostic instrumentation will be included on future flights.

Motor Contractor Assistance at Launch Preparation

The presence of a single knowledgeable motor engineer at the critical periods of launch preparation (acceptance of the motor at the launch site, igniter installation, and motor installation in the spacecraft) can eliminate expensive delays in the event of interface and handling questions, and can eliminate errors in igniter and motor installation by spacecraft and launch vehicle contractors. His presence is a valuable supplement to the skeletal written motor handling procedures. His presence can serve the useful purpose of placing proper emphasis and order of importance on the space motor as a critical subsystem. His presence can also be beneficial in the experience gained toward improvement in space motor design to make these designs more tolerant of launch site handling.

This recommendation, as Item 2 above, can be implemented immediately and at low cost per motor. It appears from current programs that the practice is now accepted by all spacecraft contractors and launch vehicle offices.

Margin Testing

Materials, components, and subsystems of these high performance motors perform satisfactorily within the design environment (and, on occasion, in an excursion from this environment) because the calculated

design requirements are adjusted upward in characteristics or dimension by a design margin. In some instances such as motor cases, a test such as hydroproof or hydroburst can establish the veracity of the margin and integrity of the design of the component or subsystem. Seldom, if ever, is it possible to demonstrate that a complete motor can perform to the calculated limits in every respect.

Progress could be made toward such demonstrations by testing or firing solid motors at or near their limits that are over age and/or surplus to present launch programs. Such motors and their test tooling exist in significant number and could be tested at modest additional expense above that already incurred in their design and manufacture. The development of an organized test plan must await assembly of the detailed information on the motors, their design margins, availability, tooling, present location and physical condition, associated costs, and so forth.

The test plan can be developed at low cost, and its preparation is underway. The cost of the actual testing and the testing schedule are yet to be estimated.

Pressure and Zone Curing

As stated previously, the participating contractors are aware of the techniques for pressure curing of motors to reduce or eliminate residual stress and strain. The zone-cure technique is in limited use and its applicability has not been fully determined. The degree of refinement of pressure-cure cycles and the extent of their applicability has not been determined. Pooling and sharing of this technology among the participants would allow application of either or both techniques to this class of motors. The present practices of the motor contractors are similar, and the success of NASA/Lewis in the preparation of a number of design criteria in areas formerly considered proprietary give hope that this can be accomplished.

The cost and schedule for this endeavor should approximate the similar efforts at Lewis--somewhat less than one man-year expended during a two year period to allow review and comment on drafts of the material submitted.

Elastomeric Chamber Insulation

The potential areas for improvement in the chamber insulation are sufficiently numerous to warrant totally new formulations, even though none of the reviewed flights suffered failure attributable to the insulation when it was used in its designed-for environment. The present qualified formulations are well characterized (except for their moisture content and its possible migration to the liner as a result of a severe concentration gradient), but they lack some features that might be developed in formulations tailored to the requirements and environment of space motors.

The formulator has some flexibility because the existing insulations were developed toward protection of the motor case by erosion resistance and char formations. The tactical rocket storage and use temperature environment was also a paramount consideration. Space motor insulation has often been determined by chamber external maximum temperature requirements to avoid thermal damage to spacecraft components. The space launch storage and use environmental temperatures are generally much less severe than those of tactical motors.

A new insulation could offer adequate erosion resistance and reduced heat transfer during postfiring heat soak, and maintain adequate physical properties throughout the space launch temperature range. In addition, it could better maintain cohesive and adhesive properties when stored as unvulcanized sheet or stock pieces. It could be formulated to vulcanize at lower temperatures so that heat-treated aluminum components would have a reduced possibility of loss of properties during integral molding process.

It could be formulated to be less sensitive to variations in surface preparation and bonding cycles. It could be formulated with materials transparent or opaque to X-ray and ultrasonic transmission so that the insulation would be more readily differentiated from chamber, liner, and propellant during NDT of loaded motors. Finally, it could be made available in a nonproprietary formulation for all rocket motor contractors.

Item 6 is expensive and time consuming in its implementation, but the inadvertent exposure of motors to exdesign low temperatures during static test and in flight during past programs points to the utility of an insulation capable of such excursions, even though it is not a stated requirement. This low temperature capability, added to the previously discussed needs of a new insulation, supports this recommendation for new formulation work.

Next in sequence of implementation are two recommendations (Items 7 and 8) that are significant in cost and not likely to yield significant improvement in reliability. A better case could be made for support of Item 8 if the weight improvement of the new safe/arm could be used in enhancing motor design margins relating to reliability.

Ignitor and Initiator NDT

The reported anomalies of ignition delays and ignition pressure abnormalities in the motor static tests in the literature reviewed were accompanied by speculation on the failure modes. These speculations questioned the quality of the conductive path and presence, quantity, and quality of the initiator pyrotechnic, the initial igniter charge and the main igniter charge or grain. The seals of the igniter pressure vessel were also questioned. Unfortunately, the NDT methods in use do not uniformly detect and measure these critical elements, and the large amount of hand labor allows the introduction of random human errors.

Although the specific flights selected for this study had no failures attributable to the igniter function, development work on NDT techniques for assembled igniters will improve confidence in their reliability. Alternatively, advantage might be taken of the limited performance life of igniters, and their design might use transparent materials that allow easier inspection.

Safe/Arm Device Development

The imposition of a range safety requirement for a safe/arm device on space motors has resulted in a weight, volume, and cost penalty for this subsystem because the "fix" was use of an older, but qualified, device. Subsequently, in several development programs for rocket motors and other ordnance, the state of the art has been advanced significantly. This progress is typified by designs shown feasible for SRAM that occupy one-half the volume and weigh only one-fifth as much as the currently used safe/arm that was qualified for the Minuteman.

The potential weight and volume savings could be readily combined with a motor chamber pressure transducer addition to maximize the benefits from the development of a new safe/arm. In the interest of future availability to all spacecraft and motor contractors, government funding of the development and qualification would be most appropriate.

The last two recommendations (Items 9 and 10) require moderate investment of cost and time for each new motor and new motor application. The expected reliability improvement is in the avoidance of future failures resulting from unanticipated thermal gradients in the motor or mismatch of tolerances between the motor and other spacecraft elements as a result of motor pressurization or thermal growth during operation.

Spacecraft/Motor Interface Review

In the initial JPL/SRI discussions of the scope of the study, it was agreed that the launch vehicle and the spacecraft environment and physical interfaces could affect the solid motor reliability, and that study of the entire system was needed. The literature review substantiated this assumption, especially in regard to simulation testing of the solid rocket motor on the ground. JPL undertook this effort and it is expected that other areas may also be uncovered in the course of the JPL study.

Analyses of Stretched Motors

Proposals for new upper stage and apogee motors in some cases obtain an increase in total impulse by adding a cylinder of uniform cross section of motor case and propellant to the spherical or $l/d < 1$ design. It does not appear in each instance that such designs can be straightforward extrapolation because of end effects and differences in motor case wall thicknesses. Therefore, sufficient new thermal and stress analyses should be performed in these instances to ensure an adequate design.

APOGEE, BOOST AND UPPER STAGE MOTOR USE

A projection of spacecraft and satellite flights was made, Table 5, to furnish guidance in the ranking of research and development recommendations. The projected use to 1975 is firm inasmuch as the programs are already funded and underway. The likely changes will be delays or deletions necessitated by budget cuts or allowed by improvements in satellite life. Another reason for delays or deletions in communication satellites will be improved utilization of existing capacity.

The 1975-80 use is less firm and is based on the combined projections of several participants in this study with modification by recent announcements in aerospace periodicals. The 1980-90 projections can only be considered as approximations because of the undeterminable impact of the space shuttle program. They are given here to illustrate the durability of demand for ABMs weighing about 1000 pounds and upper stage motors of TE-364-4 size.

Yet another major factor in these projections is the growth of foreign aerospace capability--especially in Japan and Europe. Their dependence on U.S. launch vehicles will lessen and reduce the total demand by a significant amount if their own launch vehicle development programs are successfully completed.

In summary, these projections are only of transitory value in making decisions on a limited number of research and development programs, and they do not represent a firm basis for long term decisions.

Table 5

APOGEE BOOST AND UPPER STAGE MOTOR USE THROUGH 1990

Spacecraft or Satellite	Acronym	Total S/C Weight (lbs)	Launch Vehicle	Motors			Flight Schedule							
				TE-364		ABM		1972	1973	1974	1975-80	1981-85	1986-90	
				-3	-4	Name	Weight (lbs)							
Geosynchronous Orbit														
U.K. Military Communications	SKYNET II	960	Δ2313	✓		TE-604	500		1	1	4			
NATO Phase 3 Communications		1,550*	Δ2914		✓	TBS	800				2			
Synch. Meteorological Satellite	SMS	1,325	Δ2914		✓	SVM-5	705	1	1	1	1			
Communications Technology Satellite	CTS	1,550*	Δ2914		✓	TE-616	800				5			
Communications Satellite	INTELSAT IV	3,090	ATLAS/CENTAUR			SVM-4A	1,558	3	2	2				
Canadian Communications Satellite	TELESAT	1,206	Δ1914		✓	FW-5	645	1	1	1				
System Test Satellite	STS	2,100	TITAN 3C			TBS	1,100					3	5	6
Communications Satellite	INTELSAT V	10,000	TITAN 3E/CENTAUR			TBS	5,300					4		
Small Applications Technology	SATS	600	Δ2914		✓	TBS	340					4		
Technical Data Relay Satellite	TDRS	3,700	ATLAS/CENTAUR			TBS	1,900					2		
U.S. Domestic Communications		2,000-	DELTA and ATLAS/CENTAUR			TBS	1,100-					15		
		5,000					2,800							
India Domestic IV		2,100	ATLAS/CENTAUR			TBS	1,100					3		
FAA Air Traffic Control		2,100	ATLAS/CENTAUR			TBS	1,100					4		
Aeronautical/Marine Traffic		4,200	ATLAS/CENTAUR			TBS	2,200					5		
Cooperative Applications	CAS	3,100	ATLAS/CENTAUR			TBS	1,600					2	2	1
	DWS	3,700	ATLAS/CENTAUR			TBS	1,900					2		
So. American Regional Communications		2,100	Δ2914		✓	TBS	1,100					3		
Canadian Domestic Communications		2,100	Δ2914		✓	TBS	1,100					5		
Defense Navigation Satellite	DNSS	1,600	ATLAS			TBS	840					4		
ESRO Communications Satellite		4,200	TITAN 3			TBS	2,200					1		
Navy Fleet-Sat Com	FT-SAT-COM	3,350	ATLAS/CENTAUR			TBS	1,750					1		
Medical Network		2,100	TITAN 3C			TBS	1,100					2		
Educational Broadcast		2,100	TITAN 3C			TBS	1,100					2		
						TBS = To be selected								
Interplanetary and Special Orbit														
Radio Astronomy Explorer	RAE-B	733	Δ1914		✓	TE-479	175			1		2		
Interplanetary Monitor Platform	IMP-H	860	Δ1604		✓	TE-521-5	275	1						
	IMP-J	900	Δ2314		✓	TE-521-5	275		1					
Meteorological Satellite	ESSA LOW	1,200	Δ2914		✓	None						5	5	5
Earth Resources Survey	ERTS	1,000	Δ2914		✓	None						3	2	3

* Lift weight = (S/C + motor - adapter).

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Appendix

OTHER RELIABILITY IMPROVEMENTS CONSIDERED

The initial literature review and discussions led to four preliminary recommendations that were subsequently discarded. These are:

- Space motor aging programs now in existence should have storage periods lengthened. Future aging programs should extend into the 5 to 10 year storage times.
- CTPB and HTPB propellants should be formulated to be less sensitive to cure time and temperature variations.
- Motor manufacturers should reduce their dependence on specialty materials and component fabrication by subcontracting vendors.
- A single purchase specification for ammonium perchlorate for space motor programs is needed.

Space Motor Aging Programs

Space motor development and qualification programs have included static firings of motors aged for six months to two and one-half year periods and the guiding philosophy is to use "fresh" motors for flight. The 6 and 12 month aging results have uniformly shown no significant changes, as might be confidently expected from the use of well-characterized materials and grain designs that are not demanding the ultimate achievable in propellant physical properties.

The life of satellites in space is steadily and significantly increasing, and replacement launches are being postponed accordingly. Interplanetary missions of long duration will require space motors with longer term ambient temperature aging, and there is no acceptable method of conducting accelerated aging of solid motors.

A minimum cost step toward improving this area of data deficiency would be to forego the 6 and 12-month static firings and extend storage periods toward a goal of 5 to 10 years, using existing motors. A national

inventory of unused and "space" motors might allow designation of some for periods beyond that time. A more expensive alternative is to make the additional investment for extra motors in each new motor program. Since the spacecraft contractors have a justified parochial and relatively short term interest, the government users should consider making this investment early in the new motor development and qualification programs.

In the initial discussions it was determined that interest in testing the available motors went beyond that of following the aging process, so this recommendation was incorporated in the margin testing discussions and no longer was given separate consideration.

Propellants Insensitive to Cure Cycles

Two disturbing items of information regarding propellant formulation and processing were developed in the literature review. First was the scatter of physical property data and tendency of one propellant to "postcure." Second was the processing technique of varying the cure time to achieve target physical properties. This possibly could be interpreted as undue formulation sensitivity to processing and cure conditions.

Since space motor grain designs and the space launch environment do not demand the ultimate in physical properties and there is no current effort to extract higher ballistic performance from the solid propellant, it is an opportune time to give attention to formulation changes that would result in a lowered sensitivity to cure cycle conditions to reduce the possibility of grain failures from physical properties outside of the designed for range.

It was determined from early discussions that new propellant formulation effort specifically aimed toward this class of motors cannot be justified because designs can be made around the present physical properties, and the moisture effects are understood and in control. The buyers will not accept a new formulation without manufacturing and use history. HTBP formulations that may ultimately prove useful are already under development for military application. The cost of a new formulation is typically in excess of \$500,000 and the implementation time is in excess of five years.

In-House House Materials and Fabrication

Information developed in the literature review and in current peripheral studies indicated several areas of concern regarding future solid rocket motor programs.

The monopsonistic buying practices of the government are becoming less acceptable to material and component subcontractors as they take a retrospective view of their net profits resulting from sole-source and competitive contracts to supply rocket motor manufacturers. A shrinking and inelastic market, low- or no-profit operations, unique quality assurance and certification paperwork, and susceptibility to government audit are a few of the factors leading to decisions to withdraw from this type of business. The rocket motor manufacturers generally will need to become more self-sufficient as subcontractors become unavailable.

Ammonium perchlorate (AP) producers are the most advanced in the process of disengagement from government business, possibly because of their complete dependence on the solid rocket industry for their market. Two of the four producers ceased operations in 1966, and the third has announced intent to cease AP production in 1972.

Aluminum powder does not present a general availability problem because the grades most frequently used in rocket fuels also have commercial application, and the quantities used in rocket fuels are a relatively insignificant portion of the market. On occasion it has been found necessary or desirable to use finer grades of aluminum powder to obtain the desired burning rate or to minimize the formation and deposition of slag in spin-stabilized motors or motors with deeply submerged nozzles. One source of this smaller particle size material has indicated intent to withdraw the product from the market.

Propellant processing characteristics and finished physical properties are determined to the greatest extent by the binder system, and, in turn, by the polymer. The interest of subcontractor suppliers of the CTPB and PBAN specialty polymers can be expected to track the shrinking market for solid rockets. If such suppliers do not withdraw entirely from the market, the premium for certification and quality control to aerospace criteria will be increased steadily as they correctly separate and identify the true cost of such controls.

Therefore, it would be desirable for each rocket motor manufacturer to invest now in some course of action that would yield direct and complete control of a source of polymer, if not of all the components, of the selected binder system.

This recommendation was abandoned when it became apparent in the discussions and audits that the participating motor contractors exercised close control of subcontracting vendors and made decisions on the amount of subcontracting on the basis of economics, rather than reliability.

Ammonium Perchlorate Purchase Specifications

This preliminary recommendation is based on a peripheral SRI study of the multitude of ammonium perchlorate purchase specifications now outstanding. The problem is that in 1972 it is not yet possible to chemically and physically characterize ammonium perchlorate so that its performance in solid propellant is sufficiently predictable. Otherwise identical solid propellant formulations differ in processing characteristics, burning rate, physical properties, and resistance to change during storage when AP from different production lots or different producers is used. This occurs despite the proximity of the oxidizers to each other in the chemical and physical tests now used for acceptance testing.

Perhaps some of these differences of AP performance in the formulated propellant go undetected because of the insensitivity of the test methods. The number of significant figures used in the certified analyses from the producers does not reflect the precision of the tests as performed in good commercial practice. Differences in the particle shape and friability of the oxidizer could result in significant variation in particle size distribution of the ground fraction with no change in grinding conditions. The oxidizer moisture content changes slowly during drum storage in the presence of drying agents. The specifications, as written, generally state allowable maxima for the impurities instead of ranges, and the stated maxima are liberal when compared with the certified analyses obtained on commercial production.

Particle shape, particle size distribution, and trace impurities have combined to yield AP from two sources that is not interchangeable in some propellant formulations and rocket motor programs. AFRPL has initiated a program for characterization of AP from both suppliers in an HTPB propellant. JPL has experienced differences in heat sterilization of low modulus propellants that were attributed to the as-yet undifferentiated variations in AP quality.

This recommendation was abandoned because its contribution to reliability improvement is not demonstrable. A single purchase specification for AP has not been developed in more than two decades of use of this oxidizer, and any progress toward characterization of AP that results from the current AFRPL-funded effort will be available to all users of this oxidizer.